ELECTRICAL RESISTANCE THERMOMETER AND PYROMETER*

THIS paper consists of three parts. The first treats of the experiments made by Dr. Siemens, with a view of determining the law of the variation of electrical resistance in metallic conductors, with variation of temperature, through a greater range than had been before attempted. The second describes certain instruments, by whose use this law is applied to the measurement of temperature. The third treats of a simple method of measuring electrical resistance by means of the differential voltameter.

Our author first refers to the previous experiments made by Arnsted, by his brother, Dr. Werner Siemens, and by Dr. Matthiessen, and to the law deduced by Clausius, "that the electrical resistances of metals are directly proportional to their absolute temperatures." The maximum range of these experiments was 100° C. Dr. Siemens's experiments were made upon copper, iron, steel, silver, aluminium, and platinum; the last of these has received the most attention at his hands, as, having the highest melting point, it is the most valuable from a practical point of view.

The method employed in one series of experiments was to wind metal wire upon pipe-clay cylinders, having helical grooves to prevent contact between the convolutions of the wire, and to place these, together with three delicate thermometers, in a copper vessel enclosed in a larger one containing linseed oil, and having hollow sides packed with sand to diminish sudden variation of temperature. The bath was gradually heated by means of Bunsen's burners to 340° C., or close to the boiling point of mercury, and the readings were made with a Wheatstone's bridge and delicate galvanometer. A second series of experiments was made in a heated air vessel having a metallic screen to prevent irregular losses of heat by radiation or by atmospheric currents, the other conditions being similar to those in the first series. The results obtained were found to accord generally with those of Matthiessen and the other observers within the limits of their experiments, but pointed to a different law of increase beyond those limits. The formula hitherto known as Matthiessen's is—

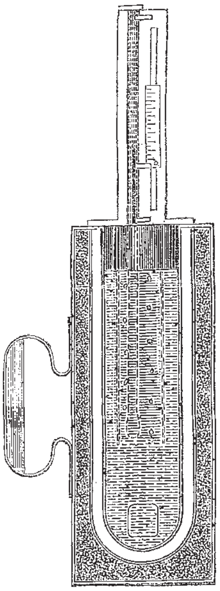

FIG. 1.

$$R_t = \frac{R_0}{1 - \cdot0037647\,t + \cdot00000834\,t^2}$$

and was the mean of the results obtained on various metals. This formula is shown to give discordant results at the higher temperatures, as the calculated resistance at 300° C. is 1·61 nearly of what it is at 0° C., whilst at 2000° C. it is ·0373, showing clearly that the formula is reliable only between very narrow limits.

We quote the author as to the law of resistance which he proposes: "Now, if we apply the mechanical laws of work and velocity to the vibratory motions of a body which represent its free heat, we should define this heat as directly proportional to the square of the velocity with which the atoms, or may be the molecules, vibrate.

"We may further assume that the resistance which a metallic body offers to the passage of an electrical impulse from atom to atom, or from molecule to molecule, is directly proportional to the velocity of the vibrations which represent its heat. In combining these two assumptions, it follows that the resistance of a metallic body increases in the direct ratio of the square root of the free heat communicated to it. Algebraically, if r represent the resistance of a metallic conductor at the temperature T, reckoning from the absolute zero, and α, an experimental coefficient of increase peculiar to the particular metal under consideration, we should have the expression—

$$r = \alpha\,T^{\frac{1}{2}}.$$

This purely parabolic expression would make no allowance for the probable increase of resistance, due to the increasing distance between adjoining particles with increase of heat, which would depend upon the coefficient of expansion, and may be expressed by $\beta\,T$, which would have to be added to the former expression. To these factors a third would have to be added expressing an ultimate constant resistance of the material itself at the absolute zero, and which I call γ. The total resistance of a conductor at any temperature, T, would, therefore, be expressed by the formula—

$$r = \alpha\,T^{\frac{1}{2}} + \beta\,T + \gamma.$$

Diagrams are given in which this hypothetical law is graphically represented, and in which its results are compared with those obtained by the experiments already cited, and by this means the following formulæ are arrived at for the different metals named:—

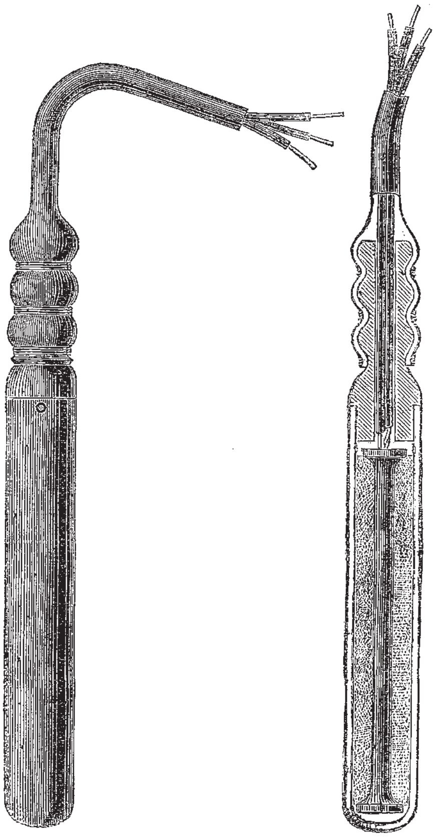

FIG. 2.

For platinum $r = \cdot0021448\;T^{\frac{1}{2}} + \cdot0024187\;T + \cdot30425$
$r = \cdot039369\;T^{\frac{1}{2}} + \cdot00216407\;T - \cdot24127$
$r = \cdot092183\;T^{\frac{1}{2}} + \cdot00007781\;T - \cdot50196$
For copper … $r = \cdot026577\;T^{\frac{1}{2}} + \cdot0031443\;T - \cdot29751$
,, iron … $r = \cdot072545\;T^{\frac{1}{2}} + \cdot0038133\;T - 1\cdot23971$
,, aluminium $r = \cdot05951436\;T^{\frac{1}{2}} + \cdot00284603\;T - \cdot76492$
,, silver … $r = \cdot0060907\;T^{\frac{1}{2}} + \cdot0035538\;T - \cdot07456$

Dr. Siemens, however, has not been satisfied with limiting his experiments to temperatures within the boiling point of mercury, but compared the law he had deduced with experimental results at higher temperatures obtained by the use of the metal ball pyrometer shown in Fig 1. Its principal parts are a metal ball, whose heat capacity equals one-fiftieth of that of an imperial pint of water, a copper vessel containing a pint of water, and a thermometer having a fixed and sliding scale with divisions of equal size, but each division in the latter being equivalent to fifty in the former. The zero of the sliding scale is fixed to coincide with the position of the mercury level in the thermometer. The ball, having been heated, is dropped into the water, whose temperature is the sum of those indicated on the fixed and sliding scales. By the use of this instrument, whose readings were compared with those of the mercury thermometer up to the boiling-point of the latter metal, results at higher temperatures were obtained. The first part concludes with several pages of tabulated results of experiments, which results are laid down in a sheet of diagrams.

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* Abstract of a Paper read at the Society of Telegraph Engineers by C. William Siemens, D.C.L., F.R.S., &c.

In the second part, Dr. Siemens describes the instruments he has designed for the measurement of temperature by electrical resistance, having first referred to the coils of silk-covered copper wire, by which he was enabled to detect a dangerous rise of temperature in the Malta and Alexandria Telegraph cable, coiled in ship's hold, and saved that cable from being destroyed. The simplest of these arrangements is shown in Fig. 2, and is employed for the measurement of temperature not exceeding the boiling point of water. Insulated wire is wound round a cylindrical piece of wood and is enclosed in a metal casing : one end is joined to a thicker insulated wire, and the other to a similar one soldered to it ; this is called the thermometric resistance coil or thermometer coil. The thermometrical comparison coil is formed of an exactly similar wire, and has an equal resistance with the other. The wire is wound upon a metal tube, and is enclosed in a protecting capsule of metal, in the open end of which is fitted a vulcanite stopper through which are passed the leading wires attached to the coil. This is placed in a movable tube having a flanged bottom and containing a mercury thermometer; the tube is immersed in a cylindrical vessel of water, wherein it is moved up and down, the flange agitating and thus equalising the temperature of the water. The thermometer coil, which may be at a distance from the place of observation, is connected with the comparison coil through a pair of equal resistances and a galvanometer. When electrical equilibrium is obtained, by adding hot or cold water to the vessel containing the comparison coil until the galvanometer needle is at the zero of its scale, it is evident that $\frac{A}{B} = \frac{T+l}{T'+l'}$ A and B representing the equal resistances, l and l' the equal resistances of the leading wires, and T T' those of the thermometer and resistance coils, or T = T', and the temperature of the water in which the comparison coil is placed will be that of the distant station.

In measuring deep-sea temperatures the coil must be so protected as to be perfectly insulated at the greatest depths, and the wire so coiled as to be effected by slight variations of temperature in its vicinity. The necessary instrument is shown in the sketch Fig. 3, which represents an insulated wire coiled on a metal tube; one end of the wire is soldered to the tube, the other to a copper wire insulated with gutta percha, and carried through a hole to the interior : over each end of the tube is drawn a piece of vulcanised india-rubber pipe, and over the whole a larger piece of india-rubber tubing, which, after being padded outside with hemp yarn, is lashed tightly with a stout binding wire. The gutta-percha covered wire is placed between the india-rubber pipes b and c, its end being soldered to one of the leading wires, the other leading wire being soldered to the brass tube. The whole is carried at the end of the sounding line, which contains the leading wires. These coils are tested under hydrostatic pressure, and accurate readings are obtained to a tenth of a degree Fahrenheit.

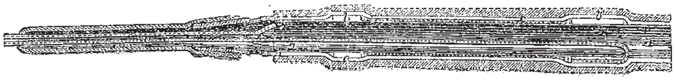

Fig. 3.

The only difficulty that has hitherto arisen in the employment of this instrument has been the obtaining of skilled observers to note with accuracy the indications of the galvanoscope on board ship.

The next instrument described is the electrical pyrometer, the coil of which is made of platinum wire, wound on a hard baked pipe-clay cylinder in which a doubled threaded helical groove is formed, and which is shown in Fig. 4.

At each end of the spiral portion B B, it is provided with a ring-formed projecting rim c and c', the purpose of which is to keep the cylinder in place when it is inserted in the outer metal case, and to prevent the possibility of contact between the case and the platinum wire. Through the lower ring c' are the small holes b b', and through the upper portion two others, a a. The use of the upper holes a a' is for passing the ends of the platinum wires through, before connecting them with the leading wires. From these two holes downwards platinum wires are coiled in parallel convolutions round the cylinder to the bottom, where they are passed separately through the holes b b'. Here they are twisted, and by preference fused together by means of an oxyhydrogen blow-pipe. At this end also the effective length and resistance of the platinum wire can be adjusted, which is accomplished by forming a return loop of the wire, and providing a connecting screw-link of platinum, L, by which any portion of the loop can be cut off from the electrical circuit.

The pipe-clay cylinder is inserted in the lower portion of the protecting case seen in Fig. 6. This part of the case is made of iron or platinum, and is fitted into the long tube, which is of wrought iron, and serves as a handle. When the lower end of the casing is of iron, there is a platinum shield to protect the coil on the pipe-clay cylinder. The purpose of the platinum casing is to shield the resistance wire against hot gases, and against accident. At the points A A, Fig. 4, the thick platinum wires are joined to copper connections, over which pieces of ordinary clay tobacco-pipe are drawn, and which terminate in binding screws fitted to a block of pipe-clay, closing the end of the tube. A third binding screw is provided, which is likewise connected with one of the two copper connecting wires, and which serves to eliminate disturbing resistances in the leading wires. The pipe-clay cylinder is, when cold, highly insulating; its conducting power increases with heat, but not to an extent to produce error, as the variation is inappreciable until a white heat is reached, but in measuring temperatures above a white heat, the indications of the instrument are slightly below the true value. In measuring temperatures with this instrument the differential voltameter is employed, a wide range of resistances being obtained ; this instrument forms the subject of the third part o this paper, to which we now refer. The theory of differential measurement and the instrument employed are thus described by Dr. Siemens :—

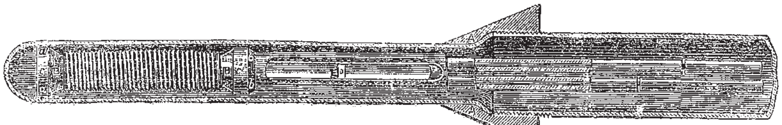

Fig. 4.

Faraday established the law that the decomposition of water in a voltameter in an unit of time is a measure of the intensity of the current employed ; or, that

$$I = \frac{V}{t};$$

—I being the intensity, V the volume, and t the time.

According to Ohm's general law, the intensity, I, is directly governed by the electro-motive force, E, and, inversely, by the resistance, R, of the electric circuit, or, it is

$$I = \frac{E}{R}.$$

Combining the two laws we have

$$V = \frac{E}{R}t,$$

which formula would enable us to determine any unknown resistance, *R*, by the amount of decomposition effected in a voltameter in a given time, and by means of a battery of known electromotive force.

Practically, however, such a result would be of no value, because the electromotive force of the battery is counteracted by the polarisation, or electrical tension, set up between the electrodes of the voltameter, which depends upon the temperature and concentration of the acid employed, and upon the condition of the platinum surfaces composing the electrodes. The resistance to be measured would, moreover, comprise that of the voltameter, which would have to be frequently ascertained by other methods, and the notation of time would involve considerable inconvenience and error. For these reasons the voltameter has been hitherto discarded as a measuring instrument, but the disturbing causes just enumerated may be eliminated by combining two similar voltameters in one instrument, which I propose calling a "differential voltameter," and which is represented in the accompanying drawing.

It consists of two similar narrow glass tubes, A and B, of about 2·5 millimetres in diameter, fixed vertically to a wooden frame, F, with a scale behind them divided into millimetres or other divisions. The lower ends of these tubes are enlarged to about 6 millimetres in diameter, and each of them is fitted with a wooden stopper saturated with paraffin and pierced by two platinum wires, the tapered ends of which reach about 25 millimetres above the level of the stopper. These form voltametric electrodes.

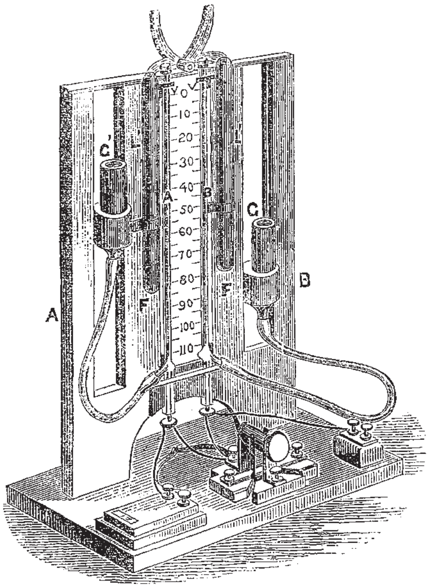

FIG. 5.

From the enlarged portion of each of the two voltameter tubes a branch tube emanates, connected, by means of an india-rubber tube, the one to the moveable glass reservoir G, and the other to G′, Fig. 5. These reservoirs are supported in sliding frames by means of friction springs, and may be raised and lowered at pleasure. The upper extremities of the voltameter tubes are cut smooth and left open, but weighted levers, L and L′, are provided, with india-rubber pads, which usually press down upon the open ends, closing them, but admitting of their being raised, with a view of allowing the interior of the tubes to be in open communication with the atmosphere. Having filled the adjustible reservoirs with dilute sulphuric acid on opening the ends of the voltameter tubes, the liquid in each tube will rise to a level with that of its respective reservoir, and the latter is moved to its highest position before allowing the ends of the tubes to be closed by the weighted and padded levers.

The ends of the platinum wire forming the electrodes may be platinised with advantage, in order to increase the active surface for the generation of the gases.

Fig. 6 represents the connections of the voltameter with the pyrometer. One electrode of each voltameter is connected with a common binding-screw, which latter may be united, at will, to either pole of the battery, whilst the remaining two electrodes are, at the same moment, connected with the other pole of the same battery; the one through the constant resistance-coil, X, and the other through the unknown resistance, X′. This unknown resistance, X′, is represented to be a pyrometer-coil.

By turning the commutator seen at Fig. 5 either in a right or left-hand direction from its central or neutral position (in which position the contact-springs on either side rest on ebonite), the current from the battery flows through the two circuits, causing decomposition in the voltameters; and the gases generated upon the electrodes accumulate in the upper portions of the graduated tubes. By turning the commutator half round every few seconds, the current from the battery is reversed, which prevents polarisation of the electrodes, as already stated.

The relative volumes, *v* and *v′*, of the gases accumulated in an arbitrary space of time within each tube must be inversely proportional to the resistances, *R* and *R′*, of the branch circuits, because—

$$v : v' = \frac{E}{R} t : \frac{E}{R'} t,$$

and, therefore,

$$v : v' = R' : R.$$

The resistances *R* and *R′* are composed, the one of the resistance *C*, plus the resistance of the voltameter *A*, and the other of the unknown resistance *X*, plus the resistance of the voltameter *B*. But the instrument has been so adjusted that the resistances of the two voltameters are alike, being made as small as possible, or equal to about 1 mercury unit, to which has to be added the resistances of the leading wires, which are also made equal to each other, and to about half a unit; these resistances may therefore both of them be expressed by γ.

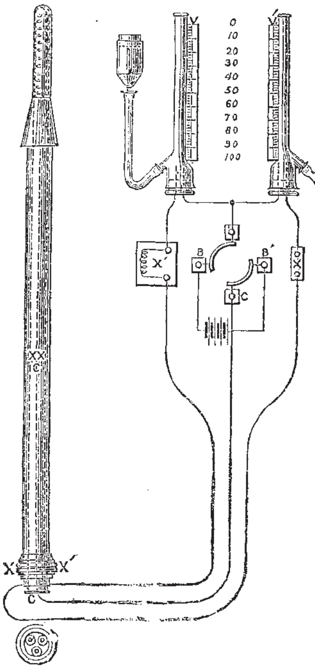

FIG.

We have, then—

$$v' : v = C + \gamma : X + \gamma,$$

or—

$$X = \frac{v}{v'}(C + \gamma) - \gamma \quad . \quad . \quad . \quad . \quad . \quad (1)$$

which is a convenient formula for calculating the unknown resistance from the known quantities *C* and γ, and the observed proportion of *v* and *v′*.

The constant of the instrument (γ) is easily determined, from time to time, by substituting a known resistance for *X*, and observing the volumes, *v* and *v′*, after the current has been acting during an arbitrary space of time, when in the above formula, γ, has to be separated as the unknown quantity, giving it the form—

$$\gamma = \pm \frac{v' X - v C}{v - v'} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The condition of equality between the internal resistances of both voltameters is ascertained by inserting equal known resistances in both branch circuits, when

$$v = v'$$

should be the result. Failing this, the balance is generally re-established by reversing the poles of the battery, the reason being that hydrogen electrodes are liable to accumulate metallic or other deposit upon their surfaces, which is effectually removed by oxygen.

When the instrument is to be worked between wide ranges of temperature, it is requisite that C should be variable, and nearly equal to X, and that γ should be very small compared with X.

By equating the values of the equations

$$X = \frac{v}{v'}(C+\gamma) - \gamma = r = {\cdot}039369\,t^{\frac{1}{2}} + {\cdot}00216407\,t - {\cdot}24127,$$

C and γ in the instruments constructed being equal to 17 and 2 units, we arrive at

$$t^{\circ}\text{Cent.} = \left\{ \left(877{\cdot}975 \times \frac{v}{v'} + 101{\cdot}80877\right)^{\frac{1}{2}} - 9{\cdot}0960553 \right\}^{2} - 274{\cdot},$$

from which a table has been prepared to be used with the pyrometer.

The precautions which have to be taken to insure reliable results in using the Differential Voltameter are:—

1st. The dilute acid employed in both tubes should be of equal strength.

2nd. After disuse, the equality of the resistances of the voltametres and connection should be verified by passing the current through them with equal resistances in each branch.

3rd. The battery power should be proportional to the resistances to be measured, whilst owing to the voltameter exercising an opposing electro-motive force by polarisation, less than five Daniell's elements should not be employed.

4th. The india-rubber pads should be smeared from time to time with a waxy substance such as resin cerate.

With these precautions the measurements of the instrument have been compared with a very perfect Wheatstone bridge arrangement, and tables of results are given showing that it can be relied upon to within one-half per cent. of error of observation. Its principal advantages are stated to be: that the resistance is measured in work done, and does not therefore depend upon a momentary observation, that it is not influenced by motion on board ship or by magnetic disturbances, and that its construction is so simple that each part can be easily examined and verified.

It is regarded, however, only as a useful adjunct to the more important subject of thermometry, which forms the principal object of this paper.

THE GIGANTIC LAND TORTOISES OF THE MASCARENE AND GALAPAGOS ISLANDS*

EVER since the foundation of Natural History Collections in Europe, naturalists had their curiosity excited by shells of Tortoises of enormous size that were brought home in vessels coming from India. From the accounts of travellers as well as from the great convexity of their shell, these tortoises were known to be terrestrial in their life, and totally distinct from the other giants of the Chelonian order, the marine Turtles. Various localities having been given as their habitat, such as the Cape of Good Hope, the Coast of Coromandel, Malacca, China, &c., the impression prevailed that they were found in many parts of India, and consequently nothing could have been more appropriate than the name given to them, *Testudo indica*.

It is not the object of the present article to treat in detail of the divergent views held subsequently by zoologists, some distinguishing several species from the difference of the form of the shell alone, others maintaining that there was one very variable species only which had been carried by ships from its native place into various parts of the globe where it became acclimatised, until Dr. Gray, the principal advocate of the latter opinion, himself was compelled to admit that there must be at least two kinds, one with a convex and the other with a flat skull. The scientific study of these tortoises may be said to have commenced with this distinction, but it commenced at a time when the work of disturbance and extermination by man had already reduced the amount of evidence so far as to well nigh bring the subject into the domain of palæontological research.

From the accounts of voyagers of the sixteenth and seventeenth centuries we learn that these tortoises were found at two most distant stations, one being the Galapagos group in the Pacific, the other comprising some of the islands of the Indian Ocean; Mauritius, Rodriguez, Aldabra, and probably Réunion. Widely different as these stations are in their physical characteristics, they had that in common, that they were, at the time of their discovery, uninhabited by man or even by any large terrestrial mammal. There is not the slightest trace of evidence that any of the intervening lands or islands have ever been inhabited by them.

At first the Tortoises were found in immense numbers and of extraordinary size. Leguat (1691) says that in Rodriguez "you see two or three thousand of them in a flock, so that you may go above a hundred paces on their backs;" and indeed, when we consider that these helpless creatures lived for ages in perfect security from all enemies, and that nature has endowed them with a most extraordinary degree of longevity, so that the individuals of many generations lived simultaneously in their island home, we can well account for the multitudes found by the first visitors to those islands. For a period of more than a century they proved to be a source of great benefit to the crews and passengers of ships, on account of their excellent and wholesome meat. In times when a voyage, now performed in a few weeks, took as many months, when every vessel, for defence's sake and from other causes, carried as many people as it was possible to pack into her, when provisions were rudely cured and but few in kind, these tortoises which could be captured in any number with the greatest ease in a few days, were of the greatest importance to the famished and scorbutic ship's company. The animals could be carried in the hold of the ship for many months without food, and were slaughtered as occasion required, each tortoise yielding from 80 to 300 pounds of fresh wholesome food; and we read that ships leaving the Mauritius or the Galapagos used to take upwards of 400 of these animals on board.

Although no account of the first discovery of the Galapagos Islands appears to have been published, so much is certain that it is due to the Spaniards, who applied the Spanish word for tortoise to this group of islands. It became the regular place of meeting and refitting to the buccaneers and whalers, who provisioned themselves chiefly with tortoises and turtles. But numerous and constant as these visits were, the reckless destruction of animal life was limited chiefly to the coast-belt, and numbers of the animals inhabiting the interior escaped; no regular or extensive settlement being attempted, the condition of the islands and of the animals inhabiting them remained in the main unaltered until the earlier portion of the present century. From the accounts of that period I select that given by Porter, a Captain in the United States Navy, as the one which contains by far the most interesting observations (Journal of a cruise made to the Pacific Ocean, New York, 1822, 8°). He found, in the year 1813, the tortoises in greater or less abundance in all the larger islands of the group which he visited, viz., Hood's, Narborough, James, Charles, and Porter's Islands. On Chatham Island he found only a few of their shells and bones, which appear to have been lying there for a long time, and possibly may have belonged to individuals transported from some other island. On Albe-

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* The substance of this article is contained in a paper read by the author before the Royal Society in June, 1874, which will appear in the forthcoming volume of the "Philosophical Transactions," and to which I must refer for the scientific portion and other details. Some facts which have come to my knowledge subsequently to the reading of this paper, are added.